Response Referee 3

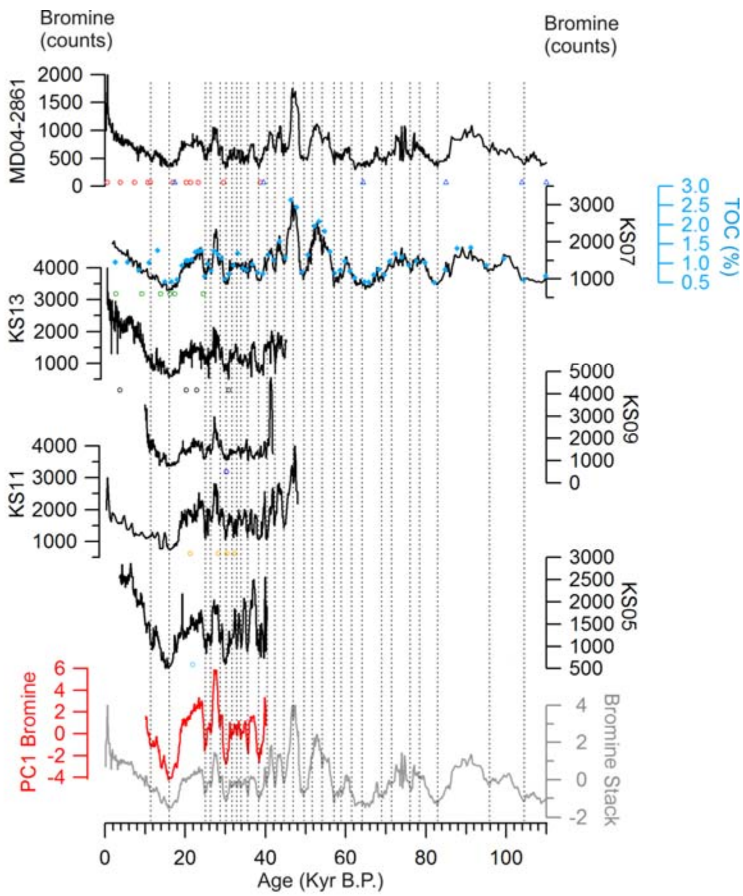
We thank the referee 3 for his review and suggestions. They will be helpful for the revision of our paper. Below, we provide point-by-point responses to the referee comments (red text).

The manuscript by Caley et al. presents a composite Bromine record from Indian Ocean, which stacks nine marine sediment cores located across the whole Arabian Sea. Following the previous study, the authors use the Bromine as the proxy of regional surface marine productivity, reflecting the intensity of Indian summer monsoon winds. Comparing the composite record to the polar ice core records from both Hemispheres, the authors suggest that during the last glacial period, the imprint of suborbital southern Hemisphere temperature change is clear, while the northern Hemisphere play a more significant role during the last deglaciation. It's good to incorporate multiple records from different locations together to investigate the common features of these records. However, the interpretation is not sound and the discussion on the orbital forcing for Indo-Asian summer monsoons is weak because of lack of reliable evidence.

Comments and suggestions

It is reasonable to use the Bromine counts as the proxy index of total organic carbon in the sediment, as the bromine counts correlates well with the total organic carbon.
However, the total organic carbon is not only affected by the surface productivity in Indian Ocean, but also altered by the preservation of the organic materials which is related to the dynamic of OMZ in Indian Ocean. The significant differences among different cores indicate that the dynamic of OMZ may play an important role in changing the total organic carbon, i.e. bromine counts. For example, the bromine counts show much weak oscillation in drilling cores KS-04, KS-07 and KS-09 than in cores KS-05, KS-11 and KS-12. Also, the differences among the stacked Bromine records and TOC record from core SO90-111KL are significant, although the authors try to link the peaks and troughs with the dashed lines, which may change the original chronology out of the range of the dating errors. So the interpretation of the Bromine counts needs to be further proved.

In the revised version, we only conserved Bromine records with the highest resolution (close to 120 years or less) to limit its potential influence on the statistical correlation (see new Fig. 3 and Table 2).



New Figure 3

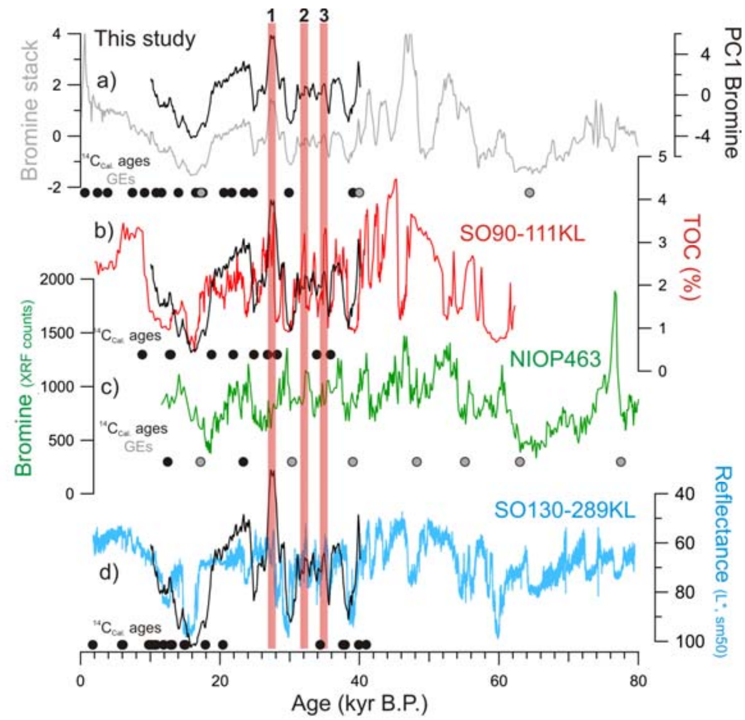
Core	Lat	Lon	Depth	Last 40 kyr resolution (yrs)	R^2 -EDML (10-16 kyr)	P-value -EDML	R^2 -EDML (16-40 kyr)	P-value -EDML	R^2 NGRIP (10-16kyr)	P-Value NGRIP	R^2 NGRIP (16-40 kyr)	P-value NGRIP
KS05	19.4	60.8	2710	90	0.41	0.00	0.09	0.00	0.16	0.00	0.03	0,05*
KS07	18.0	58.0	2209	130	0.56	0.00	0.25	0.00	0.27	0.00	0.02	0.03
KS09	21.7	61.1	3185	80	0.64	0.00	0.25	0.00	0.36	0.00	0.02	0.01
KS11	20.2	61.3	4004	65	0.24	0.00	0.20	0.00	0.01	0,50*	0.01	0.01
KS13	22.3	60.3	2678	50	0.30	0.00	0.20	0.00	0.42	0.00	0.01	0.03
MD04-2861	24.1	63.9	2049	100	0.15	0.00	0.38	0.00	0.12	0.00	0.00	0,40*
NIOP 463 (Ziegler et al., 2010)	22.5	64.0	920	160	0.01	0,70*	0.12	0.00	0.16	0,10*	0.00	0,30*
SO90-111KL (Schulz et al., 1998)	23.1	66.5	775	90	0.00	0,90*	0.36	0.00	0.38	0.00	0.06	0.00
SO130-289KL (Deplazes et al., 2013)	23.1	66.5	571	annual	0.28	0.00	0.40	0.00	0.77	0.00	0.20	0.00
PC1 Bromine				120	**0.64**	0.00	**0.30**	0.00	**0.38**	0.00	**0.01**	0.00

New Table 2

We added in the revised version in lines 205-214: *"Comparable events of higher bromine values can be observed at 20-24 kyr and centred at 27 kyr (Fig. 3). Between 30 and 38 kyr, five events with higher bromine values are documented in each record with the event centred at 37 kyr showing a more pronounced peak in core KS05. The more pronounced peak seems to be a local effect (exported production and diagenesis) as core KS13 is located in the same basin (Owen Basin) and at the same water depth than core KS05 but does not indicate a higher peak of Br (Fig. 1). Core KS09 shows much weak oscillation compared to the other cores that can also result from local effect (Fig. 3). Between 40 and 50 kyr, four comparable bromine peaks are visible in core MD04-2861, KS07 and KS11 with the more pronounced peak centred at 47 kyr (Fig. 3). Between 50 and 110kyr, similar bromine events are observed in core MD04-2861 and KS07 (Fig. 3).*"
In order to limit the smoothing effect during the stacking procedure, we used an alternative approach based on principal components analysis (PCA) with the "R" software (http://www.r project.org/) for the time period 10-40 kyr (Fig. 3). The first component (PC1-bromine) of the analysis explains 75% of the variance and confirms the common pattern between Br records as mention by reviewer 2 (Fig. 3).
Furthermore, to assure that our conclusions were not affected by the stacking procedure or PCA we had also presented statistical analyses on individual records, having independent age model (four of our records if we exclude core KS05 and KS09 that have only one 14C control point, Ziegler et al., 2010 and Schulz et al., 1998 records and Deplazes et al., 2013 record) in the new Table 2 of our manuscript. The results support our conclusion based on the initial Bromine stack (Table 2).

We also added in the revised version in lines 322-335: *"We performed regressions underlying the coefficient of determination (R2) and P-values between Arabian Sea marine records and NH NGRIP-SH EDML δ18O ice records over the intervals 16-40 kyr and 10-16 kyr (deglaciation period).*
Although the coefficients of determination and P-values between Br records, NGRIP and –EDML δ18O signals can vary (Table 2) as a consequence of the resolution and local effect for each record, statistical analyses for the interval 16-40 kyr reveal always better correlations between Br records (and PC1-bromine) and the –EDML atmospheric signal than between Br records (and PC1-bromine) and the NGRIP atmospheric signal (Table 2). The same observation is true for the Br record of Ziegler et al. (2010), the TOC record of Schulz et al. (1998) and the reflectance record of Deplazes et al. (2013) on their own age model (Table 2). Note that for the majority of these records, the resolution is high enough (lower or equal to 100 yrs) to allow comparison with the NGRIP record. This is particularly true for the record of Deplazes et al. (2013) that have an annual resolution, therefore even better than the resolution of the NGRIP record." Therefore our main conclusion stays unchanged.

We also added in the revised version a detailed comparison between the different productivity records of the Arabian Sea. This results in a new paragraph 3.3 and a revised Figure 6 (see below).



New Figure 6

We added in lines 252-307: "*At the moment, there is no clear consensus concerning the effect of oxygen on the preservation of organic matter (Cowie et al., 1999; 2005; Burdige, 2007). To investigate a potential impact of the absence of oxygen in the OMZ on the preservation of the productivity signal in the Arabian Sea, we compared different published productivity records (Schulz et al., 1998; Ziegler et al., 2010; Deplazes et al., 2013) with our results, covering various water depths (Fig. 1 and Fig. 6). We focus on the interval 10-40 kyr. PC1-bromine (mainly composed of records from below the modern OMZ) and TOC record of core SO90-111KL (Schulz et al., 1998) show a general good agreement (Fig. 6). Slight differences can be observed between 20 and 26 ka and can be related to age model uncertainties. Records can be reconciled by a time shift lower than 2kyr, in agreement with individual marine record uncertainties described previously. The only main differences in term of peaks amplitude can be observed between 32 and 35 ka (Fig. 6) with higher TOC peaks in core SO90-111KL. To investigate the origin of these differences we further compared with Br results from core NIOP463 (Ziegler et al., 2010) and results from core SO130-289KL (Deplazes et al., 2013). Core NIOP463 has a low resolution compared to the other records (Table 2) and only two 14C dates, making difficult to identify and discussed the Br peaks. On the contrary, core SO130-289KL has an annual resolution and is well constrained by 14C dating (Deplazes et al., 2013) (Fig. 6). Results of core SO130-289KL do not indicate extreme productivity peaks at 32 kyr and 35 kyr and the structure of the signal is more comparable to the PC1-bromine signal rather than to the TOC signal in core SO90-111KL. Interestingly, a major peak in organic carbon can be observed at 27 kyr in the PC1-bromine record as well as in the TOC record of core SO90-111KL but not in core SO130-289KL (Fig. 6). These tree main differences (frames on Fig. 6) between Arabian Sea productivity records cannot be attributed to a problem of resolution between records. Concerning a potential effect of the OMZ on the preservation of the productivity signal, we note that some differences exist between records located within the modern OMZ (cores SO90-111KL, SO130-289KL and NIOP463) (Figs. 1 and 6). We also note that records located below the present OMZ fit with* *some records within the OMZ during such different events (peak at 27 kyr for example) (Fig. 6). In addition, a key argument for a minor role of the OMZ in driving the preservation of organic matter is the observation that records below and within the present OMZ co-varied with other surface productivity records (Reichart et al., 1998; Caley et al., 2011; see also Pichevin et al., 2007).*

Therefore, it can be suggested that (1) the dynamics of the OMZ in the past is not the main driver of the organic carbon preservation signals observed in marine records and (2) the potential effect of bioturbation under the OMZ is weak.

As the terrestrial organic matter is poor in Br compared to the marine (Mayer et al., 2007), a preferential input or degradation of terrestrial organic matter affecting the TOC record in cores located close to the Indus river (SO90-111KL and SO130-289KL) could explained some differences with Br records (Fig. 1 and 6). However, core SO90-111KL and SO130-289KL exhibit some differences in term of amplitude of events whereas they are at the same location, close to the Indus River (Fig. 1 and 6). In addition, the similarity between PC1-bromine event at 27 kyr with that of core SO90-111KL together with the similarity between PC1-bromine event at 32kyr and 35kyr and thus of core SO130-289KL (Fig. 6) argue against a preferential input or degradation of terrestrial organic matter.

We suggest that the discrepancies between records reflect the effect of local particularities (mostly exported production, and secondly diagenesis) that can induce signal bias. If true, our strategy based on the extraction of the common variance between different records appears to be a good strategy and the obtained results more susceptible to be compared with other records. Indeed, our results based on PC1-bromine capture the peaks of core SO130-289KL at 32 and 35 kyr which are different in core SO90-111KL but also capture the major peak at 27 kyr which is visible in core SO90-111KL and in our six separated bromine records (Fig. 3) but not in core SO130-289KL.

To resume, SH ventilation changes and the dynamic of the OMZ can't be invoked as the main driver of the generation and preservation of productivity signals in the Arabian Sea. Indian summer monsoon dynamic induce variability in upwelling seems to be the good candidate to explain the productivity signals recorded."

Page 9323, Line 15-19. The authors mentioned: "Results from this study support the idea that the atmospheric d18O signal is exported by the Indian summer monsoon winds towards the Asian monsoon system, as recently showed by numerical modelling (Pausata et al., 2011; Lee et al., 2012), explaining the synchronicity between the Indian and Asian monsoon millennial events (Fig. 7)." How can this study support this idea?

My understanding is that this study only reveals that the monsoon wind over the Indian Ocean varied in a pattern similar to the Antarctic temperature changes during the last glacial and aligned with the Greenland temperature during the deglaciation. How can the variation in monsoon wind link with the precipitation 18O over the northern Indian (as mentioned in Pausata et al., 2011) and then the precipitation 18O over the East Asia? Actually, if the authors compare the Bromine record with the Hulu cave 18O record, can we find the significant similarity between these two records?

According to Pausata et al., 2011 simulations, the signal ultimately preserved as positive $\delta 18O$ excursions in the Chinese speleothems reflects variations in the $\delta 18O$ value of moisture exported by wind from India. There is no relationship between precipitation intensity in East Asia and $\delta 18O$ of speleothems. This suggests an integrated moisture transport rather than amount of local precipitations in driving the d18O signal recorded in speleothems.

Modern observations show that the ISM circulation and associated moisture penetrate northeastward, deep into East Asia. As a result, it has been argued that a significant component of EASM precipitation is derived essentially from the ISM domain.
If the ISM wind contain the SH imprint during glacial and considering the strong relationship between the ISM and East-Asia, East Asian δ18O of speleothems would contain the same SH imprint during glacial. Rohling et al., 2009 conducting a detailed analysis on East-Asian speleothems. I quote from Rohling et al. 2009 abstract: *"Previous studies have suggested a sound chronological correlation between the Hulu Cave record (East Asian monsoon) and Greenland ice-core records, which implies a dominant control of northern hemisphere climate processes on monsoon intensity. We present an objective, straightforward statistical evaluation that challenges this generally accepted paradigm for sub-orbital variability".* And *"Our analysis strongly suggests a dominant control on millennial-scale monsoon variability by southern hemisphere climate changes during glacial times when the monsoon is weak overall, and control by northern hemisphere climate changes during deglacial and interglacial times when the monsoon is strong."*
We can therefore proposed that the δ18O signal recorded in the Asian monsoon speleothem records could be exported by winds from the Indian summer monsoon region, as recently proposed in modelling exercise (Pausata et al., 2011), explaining the SH signature observed in Asian cave speleothems.

Page 9323, line 26. This study argues that the Indo–Asian monsoon can be considered as an amplifier of inter-hemispheric energy transfer at sub-orbital scale during the last glacial period. What is the original inter-hemispheric energy transfer signal, or what is forcing of the inter-hemispheric energy transfer? Can we find this amplified interhemispheric energy transfer signal in other records, such as the Greenland ice core temperature record (as amplified energy transfer will affect the temperature in Greenland, i.e., figure 8)? I think the Indo-Asian monsoon only transfer energy from southern Hemisphere to northern Hemisphere, so the word inter-hemisphere is not appropriate here.

We explained in the text: *"The asynchronous relationship between Antarctic and Greenland millennial-scale temperature changes during the last glacial period has led to the theory that the bipolar seesaw acts to redistribute heat according to the state of the Atlantic Ocean meridional overturning circulation (Crowley, 1992; Broecker, 1998). We propose that atmospheric teleconnection can amplify this process and that the Indo-Asian monsoon plays an important role.*
During SH cooling, the monsoon circulation is enhanced with important energy transfers to the NH, which can, in turn, amplify/modulate DO interstadials (Fig. 7 and Fig. 8). This atmospheric teleconnection has already been suggested for DO interstadials 12, 8, and 1 (Rohling et al., 2003)."
Indeed the Indo-Asian monsoon transfer energy from southern Hemisphere to northern Hemisphere but the term interhemispheric is used because atmospheric teleconnection and the monsoon can amplified the exchange of energy by the bipolar seesaw. The entire system of energy exchange is interhemispheric.

Why the monsoon interstadial events aligned with GIS 12, 13 and 14 are much stronger than other events and also even stronger than the Holocene? These events are not so prominent in the core NIOP 463.
Events aligned with GIS 12, 13 and 14 are much stronger than other events because the orbital forcing is particularly strong during this time interval. We observe a maximum of precession but also a maximum of obliquity (the maximum value over the last 80ka) whereas obliquity

decreases during the Holocene. As mentionned in the text *"Superimposed on the suborbital/millennial dynamics, the external (insolation) forcing contributes to Indo-Asian summer monsoon variability. Differences in the amplitude of millennial events can be observed between Indian and Asian monsoon records (Fig. 7). This could be attributed to local influence on speleothem δ18O signals, or to superimposed orbital-driven insolation variations. As long as other Asian speleothem records reveal an overall positive signal similarity (Cosford et al., 2008), the observed dissimilarity can be attributed to the effect of orbital variations."*
It is difficult to discuss events aligned with GIS 12, 13 and 14 in core NIOP463 as the Holocene part is missing. Nonetheless, events aligned with GIS 12, 13 and 14 are also much stronger in cores SO90-111KL and SO130-289KL (new Fig. 6).

Also the dominant increasing trend from 16 ka to present in this study contradicts with the previously reported Holocene monsoon records from Arabian Sea, e.g., Gupta et al., 2003 and 2005, which show a decreased trend of Indian summer monsoon during the Holocene. This discrepancy may weaken the arguments on the precessional phase difference between ISM and AIM and the discussion on this issue need to be revised accordingly.

We agree with the reviewer that the trends for the Holocene are contradictory when comparing the different records from the Arabian Sea. We note that in the recent published records of Deplazes et al., 2013, a decreased trend during the Holocene is not clear (Fig. 7). Anyway, these differences can't be invoked to address the precession phase differences between ISM and AM as the discussion of phase requires the use of at least 4 precession cycles to be significant (i.e 80ka). Given the very good correspondence between our Bromine stack and the record of Deplazes et al., 2013 in term of precession phasing on their different and respective age models (Fig. 7) and given the fact that comparable results have been obtained in core NIOP463 by Ziegler et al., 2010, we are confident in the robusness of such phase difference between ISM and AM on the precessional scale.